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# Combining operational models and data into a dynamic vessel risk assessment tool for coastal regions

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## Abstract

The technological evolution in terms of computational capacity, data acquisition systems, numerical modelling and operational oceanography is supplying opportunities for designing and building holistic approaches and complex tools for newer and more efficient management (planning, prevention and response) of coastal water pollution risk events.

A combined methodology to dynamically estimate time and space variable shoreline risk levels from ships has been developed, integrating numerical metocean forecasts and oil spill simulations with vessel tracking automatic identification systems (AIS). The risk rating combines the likelihood of an oil spill occurring from a vessel navigating in a study area – Portuguese Continental shelf – with the assessed consequences to the shoreline. The spill likelihood is based on dynamic marine weather conditions and statistical information from previous accidents. The shoreline consequences reflect the virtual spilled oil amount reaching shoreline and its environmental and socio-economic vulnerabilities. The oil reaching shoreline is quantified with an oil spill fate and behaviour model running multiple virtual spills from vessels along time. Shoreline risks can be computed in real-time or from previously obtained data.

Results show the ability of the proposed methodology to estimate the risk properly sensitive to dynamic metocean conditions and to oil transport behaviour. The integration of meteo-oceanic + oil spill models with coastal vulnerability and AIS data in the quantification of risk enhances the maritime situational awareness and the decision support model, providing a more realistic approach in the assessment of shoreline impacts. The risk assessment from historical data can help finding typical risk patterns, "hot spots" or developing sensitivity analysis to specific conditions, whereas real time risk levels can be used in the prioritization of individual ships, geographical areas, strategic tug positioning and implementation of dynamic risk-based vessel traffic monitoring.






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# 1 Introduction

The maritime surveillance systems are becoming more effective and developed for coastal regions (e.g. terrestrial and satellite-based Automatic Identification System – AIS, UAVs), and the maritime security rules are becoming more restrictive, following MARPOL convention (e.g. shift to ships with double hull). However, the increasing global ship traffic (four times as many ships now than in 1992 – Tournadre, 2014) and maritime transport of oil products (ITOPF, 2015) make it more difficult to significantly reduce the environmental, economic and social risks posed by potential spills. Additionally, the use of increasingly larger vessels (up to 100 000–150 000 t) means that if a major accident takes place, the amount of oil released could be vast.

In fact, the environmental and socio-economic issues associated to spills is and will always be a main topic: spill events are continuously happening, most of them unknown for the general public because of their small scale impact – for instance, half of the total oil spills in the marine environment come from operative discharges by shipping and in most of these cases the discharges are illegal (GESAMP, 2007). Nevertheless, some oil spills become authentic media phenomena in this information era, due to their large dimensions and environmental and social-economic impacts on ecosystems and local communities, and also due to some spectacular or shocking pictures generated (Leschine, 2002).

Consequently, the planning and prevention in the management of spill incidents at sea is extremely important in the reduction and minimization of potential impacts. Latest scientific and technological developments on coastal monitoring and operational oceanography have provided the opportunity to build more complex and integrated decision support systems for coastal risk management. The increasing operational predictive capacity of marine weather conditions (Hurlburt et al., 2009; Schiller, 2011) and better knowledge in fate and behaviour processes of pollutants spilt at sea or costal zones (Fingas, 2015; Johansen et al., 2015; Zhao et al., 2014a, b; Gong et al., 2014), together with the presence of advanced surveillance monitoring tools (Fischer





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and Bauer, 2010), can be integrated in order to provide a safer support for decision-making in emergency or planning issues associated to pollution risks.

The development of risk assessment studies have been used for multiple purposes, including contingency planning for response and preparedness, developing spill prevention measures, or evaluating oil exploration sites, etc. (Etkin, 2014).

Along the years, innovative oil spill hazard or risk assessment studies in coastal and marine environments have been published, considering historical data, reference situations, and typical or extreme scenarios (Castanedo et al., 2009; den Boer et al., 2014; Otero et al., 2014; WSP Canada Inc., 2014), revealing their vocation for supporting contingency planning and strategic decision making. Silveira et al. (2013) developed also a new method to calculate the ship risk collision, applied in the Portuguese continental shelf with AIS data, but without connection to oil spill hazard assessment or taking into consideration metocean conditions. Nevertheless, none of the previous studies were developed and applied in real-time risk assessment.

Other studies and methodologies developed dynamic approaches, with the possibility of being used in real-time support – Grifoll et al. (2010), Eide et al. (2007a, b), Bi and Si (2012). However, the method proposed by Grifoll et al. (2010) does not include a fate and behaviour oil spill model for a better determination of areas affected by oil. The work developed by Eide et al. (2007a, b) included an oil spill model, however the simulations were previously obtained, based on typical scenarios, and without considering the dynamic changing of environmental conditions. Bi and Si (2012) also presented a novel method for dynamic risk assessment of oil spill accidents based on numerical simulation, but in this case the method is only applied to on-demand spill event or scenario, instead of providing continuous risk mapping based on ship traffic.

In this work, we present an innovative and holistic methodology for dynamic shoreline risk quantification, with full integration of numerical metocean forecasts and oil spill simulations with the existing monitoring tools (AIS), and with the possibility of being used to study past periods, projected scenarios and also supporting continuous monitoring, contributing to real-time maritime situational awareness. The main purpose is to





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build a decision support system capable of quantifying time and space variable shoreline pollution risk levels, coming from ships along the coast, and combining multiple information layers:

1. instant vessel information (AIS)
2. regional statistics information on vessels accidents history, coastal vulnerabilities
3. instant metocean forecasting data,
4. continuously simulated oil spill fate and behaviour from ships along the coast.

The development of a risk assessment approach integrating economic, environmental and social aspects combined with operational oceanography and available surveillance monitoring systems is in line with the blue growth paradigm, resulting in an innovative, holistic and sustainable approach for the maritime sector.

The relevance of integrating the oil spill model and metocean data from forecasting systems in the risk algorithm is evaluated on a study area described in the next section.

## 2 Materials and methods

### 2.1 Pilot area

The whole system has been implemented and tested in the Portuguese continental shelf. This peripheral area is a high shipping density zone (more than 55 000 commercial vessels year$^{-1}$ crossing this area, and an average number of 140 ships present in the studied area, according to Silveira et al., 2013) with a complex network of routes, being an obligatory passage point between the Mediterranean Sea and Northern Europe or American Continent (see Fig. 1).

In this geographical zone, the activities in the near-shore area assume a very relevant role in the social, environmental and economic context (vast potential in natural





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resources, fishing, aquaculture, maritime commerce and port activity, leisure, sports and tourism activities).

In Portugal, the direct contribution of the maritime economy amounted to about 2.5 % of national gross value added in 2010 and 2.3 % of national employment (DGPM, 2012). Tourism, on the other hand, is gaining an important weight in the economy and is currently representing 48 % of the total employment related to maritime activities (DGPM, 2012), as the country is widely known as a sun and beach destination within Europe counting with a wide accommodation and restoration infrastructure.

The high frequency of ships navigating in the Portuguese coast, together with the Portuguese dependency on the economy of the sea and natural resources, raise the awareness for the risk of water pollution events in this area.

## 2.2 Approach

The method proposed for quantification of risk combines the likelihood of an oil spill occurring from a vessel navigating in the study area with the assessed consequences to the shoreline, where risk is the product of the probability (or frequency) of oil spill accidents from maritime traffic, times the severity (or consequences) of the events:

$$\text{Risk} = \text{Probability} \times \text{Severity} \quad (1)$$

The methodology and some of the statistic data is based on the risk assessment produced for Portugal and Galicia in the scope of EROCIPS project (Filipe and Pratas, 2007). A previous description of the risk model is available in ARCOPOL plus report (Fernandes, 2014).

The probability is based on dynamic marine weather conditions and statistical information (frequency constants for each accident type) from previous accidents. The severity of the consequences are the result of the combination of hypothetical spilled oil amount reaching shoreline and the coastal vulnerability on those affected areas.





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In order to simplify the development of the scale of risk and its values, logarithmic values are used, defined by indexes, following IMO recommendations (IMO, 2002):

$$\text{Log(Risk)} = \text{Log(Probability)} \times \text{Log(Severity)} \quad (2)$$

or

$$I_R = I_P \times I_S \quad (3)$$

The full details about the risk assessment model implemented is described in Sect. 2.7.

## 2.3 Vessel information

Variable vessel information is used in the computation of risk. The properties used are the geographical position, cargo type, speed, vessel type, weight (DWT), name and ID (MMSI and IMO number). Vessels with less than 100 DWT, passenger vessels and fishing vessels navigating outside restricted waters are not considered in this study. It is assumed that a vessel is navigating in restricted waters if distance to shoreline is not greater than 3 nautical miles, or if water depth is not deeper than 20 m.

The vessel information is obtained from AIS data. Presently the system is configured to seamlessly collect real time data from AISHUB.net or MarineTraffic API service, but the system can be easily adapted to collect information from any other online AIS data provider. The system is also prepared to import historical data.

## 2.4 Coastal vulnerability

The coastal vulnerability is used to quantify the consequences of shoreline contamination, on risk algorithm. This coastal vulnerability can be obtained from different vulnerability indices: costal sensitivity index (CSI), socio-economic index (SESI) and ecological index (ECSI). Ecological index was not included yet in the pilot area, but the risk modelling system is prepared to include it, once data is available.





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The characterization of the coastal sensitivity and socio-economic index in the pilot area (Portuguese continental coast) was made in the scope of EROCIPS project. Along with desk work, based on Aerial photos and on Google Earth, field surveys were conducted to the whole Portuguese continental shoreline. This information is available on the web through Google Earth (MARETEC, 2007), and this kml format is directly imported to the developed risk assessment tool.

The vulnerability indices obtained for the pilot area were defined with a very high spatial discretization, dividing the shoreline in multiple segments or stretches in extensions that can be as small as 200 m, realistically representing the variability of the shoreline.

#### 2.4.1 Coastal Sensitivity Index

This index (CSI) represents the quantification, in logarithmic scale, of the valuation of the environmental sensitivity (ecological, landscape) of the areas of the maritime coast and/or the surrounding waters that can be reached by sea pollution from hydrocarbons and/or other dangerous substances spills.

For the general group of areas of the maritime coast, NOAA's ESI (Environmental Sensitivity Index) was adapted for the Portuguese Continental Coast (modifications were related to the specificities of the Portuguese shoreline). The ranking of this index, which varies of 1 to 10, coincides with the scale of the NOAA's ESI (NOAA, 2002), defined to characterize zones of the shoreline in function of the following parameters:

- exposure to wave and tidal energy
- Slope of the coast (intertidal zone)
- type of substrate (size, permeability and mobility)
- biological productivity and sensitivity
- ease clean-up.





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The colours used to visualize the CSI ranking are the same as used in NOAA's ESI (a list description of CSI is included in Appendix A, Table A1).

In regions like coastal shoreline (restricted) waters, commercial ports, and all-purpose terminals, fishing ports, marinas or yacht harbours, and unrestricted waters, CSI is invariable and considered to be 6. However, as this tool is only estimating risks of shoreline contamination, coastal vulnerability indices of restricted or unrestricted waters/open sea are not considered by the risk model.

#### 2.4.2 Socio-economic Index

This index (SESI) intends to reflect the social-economic importance to the populations of the exploitation of the coastal zone under analysis (e.g. a beach not often used, or used but without significant infrastructures, and/or a beach with important economic value – restaurants, etc.). While the coastal sensitivity index CSI already considers the normal habitats for that shoreline, it does not consider other improvements that can exist in the zone and that are not specific of the characterization of index CSI, as fisheries or aquaculture, that have to be considered through the social-economic index SESI. This index varies from 1 to 5 (the complete list description of SESI is included in Appendix A, Table A2).

#### 2.4.3 Ecological Index

The ecological index (ECSI) is used to consider special protected areas that are not included in the Coastal Sensitivity Index. This index varies from 1 to 5. Although the risk model is prepared to include this ecological index, this was not established yet for the area of study – therefore, a constant value of 3 is now temporarily used as ECSI in all shoreline stretches. Presently a methodological definition of this index is being pursued in the scope of ARCOPOL platform project.





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## 2.5 Metocean data

Wind, currents, waves and visibility are taken into account for the probability of an accident, which is modified with correction factors adjusted by those meteo-oceanic conditions. These parameters can be imported to system's database in real-time from online internal or third party forecasting systems (as long as model output files are provided in native MOHID format – HDF5 – or in standard CF compliant netCDF formats, available online in web servers – preferably FTP or THREDDS catalogue). The implemented system presented at this work imports MARETEC-IST's forecast regional solutions available online in http://forecast.maretec.org and http://meteo.ist.utl.pt.

Currents and water properties are obtained from PCOMS-MOHID model (Mateus et al., 2012; Pinto et al., 2012). PCOMS is a 3-D hydro-biogeochemical model of the Iberian Western Atlantic region. Ocean boundary conditions are provided by the Mercator-Ocean PSY2V4 North Atlantic and by tidal levels computed by a 2-D version of MOHID (Neves, 2013; Ascione Kenov et al., 2014), forced by FES2004, and running on a wider region. PCOMS has a horizontal resolution of 6.6 km and a vertical discretization of 50 layers with increasing resolution from the sea bottom upward, reaching 1 m at the surface (Ascione Kenov et al., 2014).

Atmospheric conditions are provided by the meteorological forecasting system IST-MM5, using MM5 model (Grell et al.1994) with a 9 km spatial resolution. This operational model was initially implemented by Sousa, 2002, and updated in 2005 (Trancoso, 2012). This model is also used as atmospheric forcing of PCOMS-MOHID.

The wave parameters are obtained from the Portuguese wave forecasting system implemented at MARETEC-IST, using WaveWatchIII model (version 3.14 – Tolman, 2009) with a 5 km spatial resolution, and wind forcing provided by Global Forecasting System (GFS) from the National Oceanic and Atmospheric Administration (NOAA), with a spatial resolution of 0.5° (Franz et al., 2014).



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These meteo-oceanic properties are also used to feed the oil spill fate and behaviour model integrated in the system, which is used to estimate the hypothetical vessel-based spilled oil amount reaching shoreline.

## 2.6 Oil spill model

The integrated oil spill model used in this work is MOHID oil spill fate and behaviour component, integrated in MOHID lagrangian transport module, where simulated pollutants are represented by a cloud of discrete particles (or super-particles) advected by wind, currents and waves, and spread due to random turbulent diffusion or mechanical spreading. MOHID oil spill modelling component was initially developed in MOHID in 2001 (Fernandes, 2001), and along all these years the model has been operationally applied in different incidents (Carracedo et al., 2006; Janeiro et al., 2014), field exercises and studies worldwide, allowing the simulation of all major oil transport and weathering processes at sea. The source code of oil spill modelling system has been was recently updated to include full 3-D movement of oil particles, wave-induced currents, and oil-shoreline interaction (Fernandes et al., 2013), as well as blowout emissions (Leitão, 2013).

This oil spill model has the ability to run integrated with hydrodynamic solution, or independently (coupled offline to metocean models), being this last one the adopted option for integration in the developed dynamic risk tool, taking advantage of metocean models previously run, and thus optimizing the computational efficiency.

The dynamic risk tool continuously runs MOHID oil spill model to simulate hypothetical spills from multiple vessels across the coast, and then taking into account the fraction of oil that would approach the coastline.





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### 2.7 Risk model

Two different integrated risk types (they are integrated because they take into consideration different types of incidents) are computed: (a) risk of oil spill incident, (b) risk of shoreline contamination.

Both integrated risk types are variable in space and time due to variable vessel information and metocean conditions (that influence probability of an accident, as well as fate and behaviour of oil spills simulated). The simultaneous calculation of the risk posed by each vessel crossing a pilot area is integrated, allowing the generation of a dynamic shoreline risk map for that zone.

#### 2.7.1 Risk of oil spill incident

The risk of oil spill incident quantifies the severity based on vessel dead weight tonnage and vessel position, with higher or lower risk, if the vessel is navigating in restricted or unrestricted waters, respectively. This risk type does not take into consideration the effects on shoreline, and is represented in each vessel.

Different types of incidents are considered in the risk model: grounding, foundering and structural failures, collision (with a ship or with port facilities), fire and explosion, illegal and operational discharges. In order to obtain the integrated ship risk of spill incident, the partial probability and severity indices are integrated. Probability indices from the different types of incidents are summed up, and a weighted average severity index from the different types of incidents is determined. The sum of the probability indices ($I_{\sum \mathrm{P}}$) with the weighted average severity index ($\overline{I_\mathrm{S}}$) provides the integrated risk of spill incidents ($I_\mathrm{IRSI}$)

$$I_\mathrm{IRSI} = I_{\sum \mathrm{P}} + \overline{I_\mathrm{S}} \quad (4)$$

The full detailed formulation on determination of $\overline{I_\mathrm{S}}$ and $I_{\sum \mathrm{P}}$ is explained in Appendix B.



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### 2.7.2 Risk of shoreline contamination

The risk of shoreline contamination takes into account the interaction with the coastline, therefore the severity/shoreline consequences additionally include the virtual spilled oil fraction reaching shoreline and its environmental and socio-economic vulnerabilities, instead of simply considering the vessel deadweight tonnage and position. The oil reaching shoreline is quantified with an oil spill fate and behaviour model that continuously simulates virtual oil spills from the vessels included in the domain. Alternatively, a "non-modelled" shoreline contamination risk rating is computed, without using oil spill model for the determination of shoreline impact – in this case, a vessel shoreline proximity correction factor is used and subtracted to the risk value (with this correction factor decreasing as the vessel approaches the coastline). This risk type is represented in shoreline stretches, taking into consideration the effects from multiple vessels affecting that zone. The division of shoreline stretches for characterization of shoreline contamination risk is based on the same division used in the coastal vulnerability characterization.

The shoreline contamination risks provided are in fact a percentile (by default, percentile 98, but can be customized) of the shoreline contamination risks determined from the different vessels. Shoreline contamination risks below a user-defined value are not considered.

### 2.7.3 Probability

The probability/frequency of occurrence of a specific type of incident in a ship leading to an oil spill, is obtained from statistical constants (frequency of incidents per distance navigated, or annual incident frequency) corrected with a combination of a different factors identified as relevant in the generation of those incidents (e.g. visibility, currents, proximity to coast, etc.).

The choice of using probability of incidents for each vessel per distance unit navigated lay in the fact that the annual frequency of accidents is too static, i.e. if hypo-





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thetically there is a ship anchored off an entire year, it will still provide a risk similar to a ship in circulation, which is not entirely true. A dynamic probability will be inevitably achieved using frequency of accidents $km^{-1}$ navigated + distance navigated in a given period of time.

Generically, the probability of incident in a specific time period is computed like this:

$$P = C \times \Delta S \times I \tag{5}$$

where $C$ is the frequency constant (accidents $km^{-1}$), $\Delta S$ is the distance navigated by the ship (in km), and $I$ is the multiplying correction factors.

The distance navigated by the ship is obtained directly by ship velocity (from AIS data) and time step for risk analysis (defined by the end-user).

Since illegal/operational discharges occur based on human decisions, their probability is not influenced by environmental conditions. Thus, no correction factors are applied to the calculation of this probability. Also in this type of incident, the probability is not based on incident frequency per distance navigated, but in annual frequency – it is assumed that deliberate discharges occur independently of vessel speed. The probability of operational discharges ($P_{OD}$), is determined as follows:

$$P_{OD} = \frac{C_{annual}}{365} \times \Delta t \tag{6}$$

where $C_{annual}$ is the frequency constant (incidents $year^{-1}$) and $\Delta t$ is the time step used in the risk tool (in days).

A logarithmic scale from 1 to 8 was adopted for the index of probability. The correspondence between annual probability and index of probability can be represented by the following Eq. (7) (derived from the Table C1 in Appendix C), based in Filipe and Pratas (2007), and inspired by IMO recommendation (IMO, 2002):

$$I_P = \log(P_{annual}) + 6(I_{Pmin} = 0; I_{Pmax} = 8) \tag{7}$$





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The annual probability ($P_{annual}$) is based on the next equation:

$$P_{annual} = 365 \times \frac{P}{\Delta t} \tag{8}$$

$P$ is the probability obtained by the previous method explained in this chapter, for a specific time step $\Delta t$ (in days).

**a. Frequency constants**

Different frequency/probability constants of incidents are included in the risk model as a way to include some differentiation based on type of incidents and some probabilistic data obtained from statistical information on past incidents. These values can be changed by the end-user in any moment.

In this study, frequency constants of incidents per distance unit navigated are obtained from IAEA (2001), and missing constants are obtained from the combination of previous report with Lloyd's Register accidents database (relation between annual frequency constants was used to extrapolate frequency constants per distance navigated). The numerical values of the frequency constants used can be found in Appendix C (Table C2).

According to IAEA (2001), the frequency of incidents due to fire and explosion does not vary significantly with the region. Therefore, the frequency for this type of accidents per distance navigated is kept constant.

Also in the same report, there is no reference to illegal/operational discharges. For this kind of incident, annual incident frequency is assumed, since these discharges are independent of vessel speed. It is also assumed that such discharges do not occur in restricted waters.

**b. Multiplying correction factors**

Multiplying correction factors are used to modify the probabilities of spill incidents based on metocean conditions (wind velocity, currents velocity, wave height, and vis-





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ibility), proximity to coast and ship type. The correction factors are not applied to the probability of having operational/illegal discharges because these incidents are considered deliberate or independent from and not controlled by external effects. The values used can also be changed or calibrated by the end-user.

The correction factors included by default in this study were obtained from Risk Assessment Report for the Portuguese and Galician Coast – EROCIPS (Filipe and Pratas, 2007), and the values used are listed in detail in Appendix C (Tables C3 and C4). Table 1 summarizes the multiple correction factors used by each type of accident.

**c. Minimum risk/minimum probability**

A minimum or residual probability of an accident per unit time must be assumed, to avoid the determination of null or (nearly null) probabilities when vessels are anchored or moving very slowly (because the risk model computes the incident probability based on ship velocity). Even at slow motion or stopped, a ship has always a risk of a spill accident. For instance, there is still a chance of collision with another ship, or to anchor in a danger zone and eventually generate a grounding accident (depending on the weather and oceanographic conditions).

This probability is obtained in function of a minimum velocity. Below this velocity value, the vessel is assumed to have a constant accident probability. The minimum velocity is user-defined, and by default the value of $0.36\,\mathrm{m\,s^{-1}}$ was adopted (selection based on the minimum value corresponding to the lower correction factor for currents velocity).

### 2.7.4 Severity

The severity index list of hydrocarbon and other hazardous substances spills, whether in open sea or in restricted waters due to the various types of accidents, follows IMO recommendations (IMO, 2002) and is described in Filipe and Pratas (2007). A logarith-





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mic scale from 1 to 8 was adopted, following the same scale as probability index (Table D1 in Appendix D describes the details of severity index).

**a. Severity of risk of spill incident**

The severity in the risk of spill incident varies with the ship position (restricted/unrestricted waters), and with the hypothetical amount of spilt product. Typical values of amount of oil spilt are estimated based on the ship type, weight and the type of incident, in order to estimate the severity index of spill incident ($I_{SSI}$) according to the values in Filipe and Pratas (2007). Further detailed information on the formulations used are listed in Appendix D, Tables D2 and D3.

**b. Severity of risk of shoreline contamination**

As mentioned before, the risk of shoreline contamination from each vessel considers the risk of spill incidents plus the interaction with the coast, taking into consideration the coastal vulnerability, and the potential contamination in the near-shore. This potential contamination is computed by two different approaches: by estimating the oil fraction reaching the coastline – method herein called as “modelled” risk of shoreline contamination; or alternatively by a correction factor based on ship distance to coastline – method herein called as “non-modelled” risk of shoreline contamination.

In both approaches (modelled and non-modelled), the computed severity index of shoreline contamination ($I_{SSC}$) includes the severity index of risk of spill incident ($I_{SSI}$) mentioned in the previous section, with a weight of 50 %. The remaining 50 % of severity are obtained from the coastal vulnerability index ($I_V$), as expressed by the next formula:

$$I_{SSC} = 0.5 \cdot I_{SSI} + 0.5 \cdot I_V \quad (9)$$



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Where coastal vulnerability index can be represented as an arithmetic mean from the different coastal vulnerability indices:

$$I_V = \frac{8}{5} \cdot \left( \frac{0.5\mathrm{CSI} + \mathrm{SESI} + \mathrm{ECSI}}{3} \right) \tag{10}$$

The fraction 8/5 is used to convert the vulnerability index scale (from 1–5 to 1–8), to the same scale adopted in severity of spill incident, as well as in probability index. CSI is multiplied by 0.5 to convert the scale from 1–10 to 1–5 (as adopted in SESI and ECSI).

For non-modelled risk, a vessel shoreline proximity correction factor is subtracted to the severity of spill incident index (with this correction factor decreasing as the vessel approaches the coastline), as can be shown in the next equation:

$$I_{\mathrm{SSC(non\text{-}modelled)}} = I_{\mathrm{SSC}} - F_{\mathrm{SS}} \text{ with } F_{\mathrm{SS}} \leq I_{\mathrm{SSC}} \tag{11}$$

The determination of this factor depends on distance between spill site and shoreline, and on type of oil product/ship type (further details in Table D4).

For modelled risk, a modified severity of spill incident is adopted, in a more complex and realistic approach to determine the impact risk of oil spills on the shoreline, since fate and behaviour of oil spilled is taken into account, using MOHID oil spill model, as described in Sect. 2.6. The modified severity of spill incident is obtained by using the regular equation for severity of spill incident in restricted waters (Appendix D, Table D3), but with a modified amount of oil spill ($Q^*$) used instead of $Q$, which is computed as follows:

$$Q^* = \frac{Q \times M}{L_{\mathrm{stretch}}} \times L_{\mathrm{unit}} \tag{12}$$

$M$ is the modelled ratio of oil reaching near the shoreline stretch in a user-specified time period, $L_{\mathrm{stretch}}$ is the shoreline stretch extension (m), and $L_{\mathrm{unit}}$ is the shoreline distance





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unit used (by default is 100 m, but end-user can change this value). $Q$ is the amount of oil based on ship type, weight and the type of incident. Thus, $Q^*$ is the maximum amount of oil spilled reaching near the shoreline stretch per shoreline extension unit, in a certain time period. An increase in $L_{\text{unit}}$ will generate higher severity indexes, so this value needs to be properly calibrated.

The quantification of modelled maximum oil contaminating a specific shoreline stretch is based on the maximum amount of oil present inside an area near the referred shoreline stretch. The definition of this "near-shore" area for each shoreline stretch is based on the distance to the shoreline stretch; thus, if the modelled oil reaches this near-shore area, is assumed as relevant to the quantification of shoreline contamination risk. The near-shore distance is user-defined, and by default it is assumed a value of 2000 m from the coast. The time period used in the quantification of maximum oil spilled reaching near the shoreline stretch has a default value of 24 h (configurable). Updates and new oil spill simulations from updated vessel positions are made every hour (this value is also configurable). The oil spill model simulations are made assuming always the same oil product released. The oil product included in the risk model (Carpinteria, medium oil from Group III) was chosen based on the profile of being a "worst case scenario" for shoreline contamination, being a crude product from oil group III with low weathering effects along time.

#### 2.7.5 Risk matrix

The risk matrix is the result of crossing both probability and severity indices, in order to obtain a risk rating – Table 2. The sum of both indices generates a risk index classification scale between 2 and 16. These values are categorized with different risk levels and corresponding colours, as described in Table 3.

Independently of the integrated risk types applied (e.g. risk of spill incident; modelled risk of shoreline contamination; non-modelled risk of shoreline contamination), the same risk matrix should be applied.





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In the case of shoreline contamination risk, at the present stage of the work, the visualization of risk values in the implemented software tool follows a continuous risk scale (bounded by the same limits as defined in the risk matrix categorization scheme), instead a categorized scale, and using a different colour pattern from the proposed in Table 3. This initial implementation was to facilitate the visualization of variability in shoreline risk levels during the development period. In the future, the visualization of this risk level will be updated to the categorized view and using the same colour pattern defined and presented in Table 3.

No risk acceptance/tolerability criteria were defined in the present work.

## 2.8 Development of software

This risk assessment methodology has been implemented as a plugin from MOHID Studio, which is a GIS desktop interface that can also be used to run MOHID water modelling system. The system has been entirely developed in c#.NET language, using SQL Server components and MOHID model.

The main philosophy of the software architecture was to create separate layers, allowing distributed tasks in different processes or computers, and a lighter graphic user interface (GUI). The general information workflow in the software framework is presented in Fig. 2. According to this, the main software framework is composed by four main components, exchanging information between them:

- an SQL Server or SQL Lite database, where all the data and meta-data is stored (metocean model outputs are not stored; only indexed);
- a desktop service (Action Server), which is continuously loading/downloading updated data from different data sources (AIS data, metocean model outputs, etc.), managing MOHID oil spill model, processing all information (and computing risk levels) and storing data on database;





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– MOHID oil spill project/executable file, which is continuously generating and running virtual oil spill simulations based on ship positions, and on instructions managed by Action Server desktop service.

– A Graphic User Interface (MOHID Studio), directly connected to the database, and showing requested data to the end-user. MOHID Studio can also be used to configure Action Server, and to run on-demand risk assessment tool for specific periods.

MOHID Studio and Action Server don't need to be running on the same computer. The software architecture has also been developed to enable the publication of real-time risk mapping data in external platforms, including WMS layers, to facilitate the interoperability of the system.

## 3 Results

The risk modelling tool was tested in the pilot area, allowing to understand the applicability of the system in both operational and planning support, as well as to identify and correct any limitations. Along with these applicability and usability tests, the system is also being subject to results analysis and evaluation, in order to eventually define additional calibration procedures. In this section, the response of the proposed risk model to different metocean conditions is evaluated in the pilot area, and the graphic user interface developed in this work is also presented.

### 3.1 Graphic user interface

The risk modelling tool is able to run in continuous mode, allowing the user to follow in real-time the ship traffic and specific vessel details, the evolution of risks crossed with background dynamic web maps (e.g. Google maps, Bing Maps, Open Street Maps) and many other geographic layers and features (Fig. 3) – e.g. visualizing metocean fields,





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topography, running oil spills on-demand, etc. When zooming the view, it is possible to check the very high level of resolution of the vulnerability indices and the associated risk levels being computed (Fig. 4).

### 3.2 Ship incident risk

Metocean conditions have direct effect on risk of ship incident, because they can influence the probability of an accident occur, according to the methodology proposed. These effects are included in the risk model through categorized correcting factors based on the range of metocean conditions.

One of the exercises performed in this study was to analyse the evolution of ship incident risks according to some of these metocean conditions used, organized in the same classes as the ones used in the correcting factors. In Fig. 5, ship incident risk levels are shown in different colour classes for different instants, together with wave model data (Fig. 5a and b) and wind speed (Fig. 5c and d) used in the risk model. Generally, the lower ship incident risk levels (in green) are present in ships crossing geographical areas where wind or wave conditions belong to lower classes. The same behaviour can be seen with vessels with higher incident risk levels – they tend to be determined in vessels crossing areas where wind speed or significant wave height are greater. It is also clear in Fig. 5 that the presence of a ship in different wave classes can contribute more significantly for different risk levels than wind speed – this is due to the fact that the wind multiplying correcting factor varies from 0.8 to 2, while the wave correcting factor used varies from 0.1 to 1 or 0.22 to 1.78 (detailed values on correcting factors used can be consulted in Appendix C).

A better evaluation of the importance of metocean conditions in the risk model can be tested using different metocean conditions for the same ship positions. Figure 6 illustrates the ship incident risk levels using different metocean conditions (6 months later), and exactly the same ship information as used in Fig. 5. Figure 6 clearly shows the dynamic change of risk levels directly affected by the wind and waves, for the same vessel traffic. Comparing Fig. 6 with Fig. 5 it is clear the different ship risk levels. The





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effects of the other environmental conditions (visibility and surface water velocity) are similar to the properties illustrated here.

### 3.3 Shoreline contamination risk

When compared with ship incident spills, the evaluation of shoreline contamination risk from spills is more complex, as this parameter depends additionally on the coastal vulnerability indices, and is a result of an integration of risks from the different ships affecting each shoreline stretch. While it is easy to find different shoreline risk levels along the coast (e.g. Fig. 3), it can be difficult to evaluate and study the dependence of risk model on metocean conditions. In order to achieve this objective, an initial study was performed, to evaluate the relevance of coastal vulnerability in the risk model. Two different locations with exactly the same coastal vulnerability were studied in detail (Fig. 7), after running the system for a one-week period (18 January 2013 and 25 January 2013), and generating model risk outputs every 6 h. Both shore locations are subject to different metocean conditions and different vessels in the proximity, which can affect the evolution of shoreline contamination risk along time. The metocean conditions (from the models described in Sect. 2.5) used in both locations are illustrated in Fig. 8.

As can be seen in Fig. 9, differences could be found in the risk along time. Risks are larger in P1 (Praia Azul), which is subject to rougher metocean conditions. Two peaks are identified in risk levels in 19 and 23 January, in agreement with the peaks visible in Fig. 8.

A second analysis was performed to evaluate the different response from the risk model to two different metocean conditions using the same vessel information in both runs. The risk model was run every 6 h between 18 and 25 January 2013 (winter conditions), and between 18 and 25 June 2013 (summer conditions). The AIS vessel information used in both runs was recorded between 18 and 25 January 2013. The temporal evolution of the different shoreline contamination risks along the coast was integrated in the form of instant mean averages and maximum values, illustrated in Fig. 10. The





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variations and differences between shoreline contamination risk levels in winter and summer conditions identified in Fig. 10 can only be explained by the variation in metocean model conditions, since all the other conditions were kept constant. The image also provides information about the maximum values, showing the dynamic variation along the coast. In general, risk values are greater in winter conditions, as expected, although a more significant difference would be anticipated. Additionally, the rougher metocean conditions previously identified in 19 January are responsible for the peak in shoreline contamination risk for that day, in winter conditions.

### 3.4 The role of oil spill model

Two different tests were performed to evaluate the relevance of having an oil spill model integrated in this risk modelling tool.

First, it is important to evaluate the risk model response to different environmental conditions, favourable or unfavourable to shoreline spill contamination. Two different modelling scenarios were defined in this scope: the same ship position and metocean conditions were used in both scenarios, except wind direction (wind magnitude was not modified). The onshore wind scenario was set with a wind direction of 240°, favourable to transport oil to the near-shore. The offshore wind scenario was set with a wind direction of 60°, favourable to transport oil to the open ocean and far away from the coast. The risk model was then run for the whole pilot area for the two previously mentioned scenarios in different time instants along one day, and shoreline contamination risk levels for each time instant were integrated in mean and maximum values. Since the developed risk model includes two different methods to compute the shoreline contamination risk (estimation of oil reaching the shoreline based on oil spill model – "modelled" approach; or based on ship proximity to shoreline – "non-modelled" approach), the previous modelled scenarios are also interesting to evaluate the relative dynamic response of the "modelled" shoreline contamination risk against the "non-modelled" approach, which therefore is independent of wind or current directions.





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The second test consisted in understanding how significant is to integrate the oil spill specific weathering processes (mainly the oil spreading, evaporation, dispersion and emulsification) in the risk model, instead of simply using a generic lagrangian model. To fulfil this objective, an additional run was included, turning off the oil spill weathering processes in the onshore wind scenario.

The four different types of shoreline contamination results (non-modelled approach; on-shore wind scenario; offshore wind scenario; on-shore wind scenario with no oil weathering processes) were organized in 2 different charts – mean and maximum values –, available in Fig. 11. Results allow to firstly understand the relevance of including an oil transport model in the risk approach, mainly because it reduces the predicted risk according to favourable metocean conditions (in this case, the wind direction) – the difference between on-shore wind scenario and the others is very significant. Second, it can be seen that the developed model risk does not take advantage of modelling the oil weathering processes, as the difference between onshore wind scenario with and without oil weathering processes is not relevant. It could be expected that the weathering processes would reduce the amount of oil reaching the shoreline, therefore, reducing the risk of contamination, however results only reflect that very subtly. However, since the oil product used in the risk model (a medium crude oil named Carpinteria) has almost null dispersion and emulsification, and relatively low evaporation when compared with other products, the comparison of results with and without including weathering processes become almost insignificant. This could be changed by using a different oil product (more influenced by weathering processes) in the risk model.

## 4 Discussion

The work developed in this study aimed the conceptualization, development and implementation of a novel holistic methodology for dynamic spill risk assessment from ship traffic, fully integrated with metocean and oil spill forecasting systems, and able to be used in real-time (providing support to monitoring activities) and on-demand situations (supporting contingency planning). These objectives were fully accomplished, since the risk methodology was fully implemented in a software tool, and is being tested in a pilot area by the authors of the project as well as the Portuguese Maritime Authority – DGAM-SCPM.

The software system has been designed to be easily transferable to other areas, adopting generic approaches to download specific data layers (e.g. metocean forecasting system, AIS data, etc.), and being easily user-customized in terms of risk model parameterization. The possibility of running the risk model in a central server and providing outputs to external platforms following OGC standards, increases the interoperability of the system.

The role of different variables in the risk model was presented with specific examples, with special emphasis on the relative significance of metocean and oil spill modelling systems integrated for the pilot area. The results from the risk modelling software tool are in agreement with what was expected from the proposed methodology for risk. Using an oil transport model (together with metocean modelling systems) in the estimation of the risk of oil reaching the coastline can provide a more robust and dynamic risk assessment. The results presented here have shown that the mere fact of having intensive ship traffic in the proximity of some coastal areas does not necessarily mean that the risk of shoreline contamination is high, depending on the instantaneous metocean conditions. If they are favourable to transport an eventual oil spill to offshore, the risk of shoreline contamination will be low. Also, if the metocean and the sea state conditions are stable and not extremely rough, the probability of having ship accidents will be lower – and the risk of having ship incidents will be reduced, even if the ship traffic is intense.

Nevertheless, the inclusion of oil weathering processes in the determination of shoreline contamination risk does not seem to generate substantial differences. The possibility of further calibration in risk model, in terms of probability (using different correction factors) and consequences (e.g. increasing the relative weight of oil spill model re-





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sults in the risk model, and using different oil products in the spill simulations) can be performed in the future, in order to improve and fine-tune the expected results.

Additionally, it should be noted that the results investigated in this study were mainly focused in the testing and evaluation of the risk model dynamic behaviour and response to the different variables, and somehow comparing amplitude of risk values along the pilot area. The evaluation or full calibration of absolute risk values or the evolution along time, for longer periods was out of the scope at this stage. This type of study is expected to be pursued in the future, for the same pilot area included in this work.

Independently of the methodology developed and the results achieved with this study, a number of assumptions, limitations and lack of data were identified as relevant for improving the risk model:

- Using frequency constants to estimate probability of having incidents may need continuous and periodic update, because the continuous changes in the ship industry (e.g. obligation of double hull ships, mega-tankers, maritime surveillance, etc.) can change the probability of having incidents.
- The coastal vulnerability indices included should also be continuously updated and reviewed to reflect the present situation in terms of environment and socio-economic aspects of the coast.
- Several research work has been developed for estimating the probability of ship-to-ship collisions using more complex approaches (e.g. Silveira et al., 2013), however these algorithms were not included yet in this risk model.
- In the risk model adopted, there is no differentiation between identical ships from different countries, inspected at different ports, constructed or managed by different companies, or with different number of deficiencies detected in the recent past. This information is presently available online through EMSA's THETIS system, and in the future can be seen as a relevant added value for integration in the risk model, if possible.





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- The actual volume of contaminants, and product type transported by each ship is not included in the risk model, since the information is not publicly available (an approximation based on ship type and dead weight tonnage is adopted). This information would be rather important to improve the realistic quantification of estimated risk.

- No risk acceptance or tolerability criteria was defined in the present risk model. The future definition of these tolerability criteria will facilitate the adoption of mitigation measures in case of unacceptable/intolerable risks detected.

Aside from these identified considerations, the work presented here opens interesting opportunities for the future both in terms of risk planning and monitoring activities. A tool like this can improve the decision support model, allowing the prioritisation of individual ships or geographical areas, and facilitating strategic and dynamic tug positioning. The possibility of being used for past or hypothetical scenarios may provide an interesting tool not only for identifying "hot-spots" in terms of shoreline contamination risk, but also to estimate future situations like the increasing of ship traffic or the size and cargo transported by the ships. Furthermore, the same risk model approach can considered in the future to estimate other types of environmental threats, including impacts from spills in offshore platforms, impacts from onshore activities and industries involving discharges to the water environment, or even the environmental impact of maritime transport emissions on coastal air quality.

## Appendix A: Coastal vulnerability indices

This section provides additional detail about the classification adopted for the coastal vulnerability indices adopted in the pilot area, namely the coastal sensitivity index (CSI) and the socio-economic index (SESI).





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## Appendix B: Background on risk of spill incident

Table B1 describes the types of incidents considered in the risk model, as well as the nomenclature used.

In the determination of these risk indices for each type of incident, generic risk formula (sum of probability and severity indices) applies. Per example, for ships navigating in restricted waters, next formula represents the risk of spill incident from a ship-to-ship collision:

$$I_{\mathrm{RSI\_CS2S\_restricted}} = I_{\mathrm{P}_{\mathrm{CS2S\_restricted}}} + I_{\mathrm{S}_{\mathrm{CS2S\_restricted}}} \tag{B1}$$

Where $I_{\mathrm{P}_{\mathrm{CS2S\_restricted}}}$ and $I_{\mathrm{S}_{\mathrm{CS2S\_restricted}}}$ are the probability index and severity index (respectively) for ship-to-ship collision in restricted waters.

Integrated risk index is also determined ($I_{\mathrm{RSI}}$), which means that we can also estimate the risk of an incident of a specific ship, independently of the type of incident. This integrated risk index is a sum of the various probability indices ($I_{\sum \mathrm{P\_restricted}}$) with the weighted arithmetic mean of the severity indices ($\overline{I_{\mathrm{S\_restricted}}}$) from the different types of incidents.

Thus, if a ship is navigating in restricted waters:

$$I_{\mathrm{IRSI\_restricted}} = I_{\sum \mathrm{P\_restricted}} + \overline{I_{\mathrm{S\_restricted}}} \tag{B2}$$

where $I_{\sum \mathrm{P\_restricted}}$ is computed as follows:

$$I_{\sum \mathrm{P\_restricted}} = f\left(P_{\mathrm{CS2S\_restricted}} + P_{\mathrm{CPF\_restricted}} + P_{\mathrm{Gr\_restricted}} + P_{\mathrm{F\&\,E\_restricted}}\right) \tag{B3}$$

where $P_{\mathrm{CS2S\_restricted}}$ is the probability of ship-to-ship collision in restricted waters; $P_{\mathrm{CPF\_restricted}}$ is the probability of collision to port facilities in restricted waters; $P_{\mathrm{Gr\_restricted}}$ is the probability of grounding in restricted waters; $P_{\mathrm{F\&\,E\_restricted}}$ is the probability of fire and explosion in restricted waters





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$\overline{I_{S\_restricted}}$ is computed as follows:

$$\overline{I_{S\_restricted}} = \frac{(P_{CS2S\_restricted} \times I_{S_{CS2S\_restricted}}) + (P_{CPF\_restricted} \times I_{S_{CPF\_restricted}})}{\sum P_{restricted}} + \frac{(P_{Gr\_restricted} \times I_{S_{Gr\_restricted}}) + (P_{F\&\ E\_restricted} \times I_{S_{F\&\ E\_restricted}})}{\sum P_{restricted}} \quad \text{(B4)}$$

Where $\sum P_{restricted}$ means the sum of probabilities in restricted waters.

Alternatively, if a ship is navigating in unrestricted waters, the same approach is followed:

$$I_{IRSI\_unrestricted} = I_{\sum P\_unrestricted} + \overline{I_{S\_unrestricted}} \quad \text{(B5)}$$

Where $I_{\sum P\_unrestricted}$ and $\overline{I_{S\_restricted}}$ mean the sum of probability indices and the weighted arithmetic mean of severity indices, both in unrestricted waters. $I_{\sum P\_unrestricted}$ is computed as follows:

$$I_{\sum P\_unrestricted} = f(P_{CS2S\_unrestricted} + P_{Fo\_unrestricted} + P_{GDN\_unrestricted} + P_{DG\_unrestricted} + P_{F\&\ E\_unrestricted} + P_{IOD\_unrestricted}) \quad \text{(B6)}$$

Where $P_{CS2S\_unrestricted}$ is the probability of ship-to-ship collision in unrestricted waters; $P_{Fo\_unrestricted}$ is the probability of collision to port facilities in unrestricted waters; $P_{GDN\_unrestricted}$ is the probability of grounding in unrestricted waters; $P_{DG\_runestricted}$ is the probability of fire and explosion in unrestricted waters; $P_{F\&\ E\_unrestricted}$ is the probability of fire and explosion in unrestricted waters; $P_{IOD\_unrestricted}$ is the probability of fire and explosion in unrestricted waters.

$\overline{I_{S\_unrestricted}}$ is computed as follows:

$$\overline{I_{S\_unrestricted}} = \frac{(P_{CS2S\_unrestricted} \times I_{S_{CS2S\_unrestricted}}) + (P_{Fo\_unrestricted} \times I_{S_{Fo\_unrestricted}})}{\sum P_{unrestricted}} + \frac{(P_{GDN\_unrestricted} \times I_{S_{GDN\_unrestricted}}) + (P_{DG\_unrestricted} \times I_{S_{DG\_unrestricted}})}{\sum P_{unrestricted}} + \frac{(P_{F\&\,E\_unrestricted} \times I_{S_{F\&\,E\_unrestricted}}) + (P_{IOD\_unrestricted} \times I_{S_{IOD\_unrestricted}})}{\sum P_{unrestricted}} \quad \text{(B7)}$$

Where $\sum P_{unrestricted}$ means the sum of probabilities in unrestricted waters.

## Appendix C: Background on probability estimation

To estimate the index of probability, frequency constants obtained from reported spill incidents are used. Table C2 lists the different frequency constants (per distance unit navigated or annual frequency for illegal/operational discharges) for the various types of incidents considered, whether in restricted or in unrestricted waters.

The probability of spill incidents is influenced by certain conditions that can reduce or increase the probability. The developed risk model includes correction factors to take into consideration these conditions. The following Tables C3 and C4 express the correction factors adopted.

## Appendix D: Background on severity estimation

The Table D1 shows correspondence between severity/consequences and index of severity, obtained from Filipe and Pratas (2007), and inspired by IMO recommendation (IMO, 2002).





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Table D2 illustrates how to determine the amount of oil spilled ($Q$) based on dead weight (DW) and ship type, and Table D3 expresses the methods for determination of severity indices based on the oil amount computed in Table D2. The equations from D2 and D3 were obtained from Filipe and Pratas (2007).

The computation of severity of non-modelled risk of shoreline contamination includes the subtraction of a correction factor ($F_{SS}$) that depends on distance between spill site and shoreline ($D_{SS}$), and on type of oil product/ship type, as expressed in Table D4. The values used here are based on Filipe and Pratas (2007). Since in that report, the correction factor was applied in a scale between 1 and 15, and in this work the correction factor is applied in severity index, between 1 and 8, a multiplying factor of $\frac{8}{15}$ is applied to transform the correction factor to the appropriate scale.

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**Table 1.** Summary of multiple correction factors used by each type of accident ($I_{curr}$: correction factor due to currents; $I_{wind}$: correction factor due to wind; $I_{prox}$: correction factor due to proximity to coast; $I_{ship}$: correction factor due to ship type; $I_{visib}$: correction factor due to visibility; $I_{wave}$: correction factor due to waves).

<table>
<tr><th colspan="2">Restricted Waters</th><th colspan="2">Unrestricted Waters</th></tr>
<tr><th>Type of Accident</th><th>Correction Factors ($I$)</th><th>Type of Accident</th><th>Correction Factors ($I$)</th></tr>
<tr><td>Ship to Ship Collision</td><td rowspan="2">$I_{curr} \times I_{wind} \times I_{prox} \times I_{ship}$</td><td>Ship to Ship Collision</td><td>$I_{curr} \times I_{wind} \times I_{visib} \times I_{wave}$</td></tr>
<tr><td>Collision with Port Facilities</td><td>Foundering</td><td>$I_{wave} \times I_{prox}$</td></tr>
<tr><td rowspan="2">Grounding</td><td rowspan="2">$I_{curr} \times I_{wind} \times I_{ship}$</td><td>Grounding During Navigation</td><td>$I_{curr} \times I_{wind} \times I_{visib} \times I_{wave} \times I_{prox}$</td></tr>
<tr><td>Drift Grounding</td><td>$I_{curr} \times I_{wind} \times I_{wave} \times I_{prox}$</td></tr>
<tr><td>Fire/explosion</td><td>$I_{curr} \times I_{wind} \times I_{prox} \times I_{ship}$</td><td>Fire/explosion</td><td>$I_{curr} \times I_{wind} \times I_{prox} \times I_{ship}$</td></tr>
</table>

**Table 2.** Risk matrix based on probability and severity indices.

| Risk Index ($I_R$) | | Severity Index ($I_S$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Probability ($I_P$) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |



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**Table 3.** Classification of risk levels ($I_R$) and corresponding representation with colour.

| Level of Risk | Colour | Risk Index $I_R$ |
|---|---|---|
| Very low or insignificant | Dark green | 0 to 6 |
| Low or minor | Light green | > 6 to 8 |
| Medium or moderate | Yellow | > 8 to 10 |
| High level or serious | Orange | > 10 to 12 |
| Very high or critical | Red | > 12 to 16 |





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**Table A1.** Classes used for costal sensitivity index (CSI).

| Colour | CSI | Colour code (RGB) | | | CSI and type of shoreline |
|---|---|---|---|---|---|
| | | R | G | B | |
| | 1 | 119 | 38 | 105 | 1A: exposed rocky shores<br>1B: Exposed, solid man-made structures |
| | 2 | 174 | 153 | 191 | Exposed Wave-cut Platform in Bedrock, Mud, or Clay. Medium slope |
| | 3 | 0 | 151 | 212 | Exposed fine to medium-grained sand dissipative beaches |
| | 4 | 146 | 209 | 241 | Exposed beaches with coarse grained or fine to medium-grained sand; sheltered beaches with fine grained sand |
| | 5 | 152 | 206 | 201 | Mixed sand and gravel beaches |
| | 6 | 0 | 149 | 32 | 6A: Gravel beaches<br>6 B: Riprap |
| | 7 | 214 | 186 | 0 | Exposed tidal flats |
| | 8 | 225 | 232 | 0 | 8A: Sheltered scarps in bedrock, mud or clay<br>8B: Sheltered, solid man-made structures |
| | 9 | 248 | 163 | 0 | 9A: Sheltered tidal flats<br>9B: Sheltered low banks |
| | 10 | 214 | 0 | 24 | Salt and brackish waters marsh, freshwater marshes, swamps, mangroves or scrub wetlands |





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**Table A2.** Classes used for socio-economical index (SESI).

| SESI | Description |
|---|---|
| 1 | Area of none or very low importance in terms of environmental resources, leisure and other sea-related activities. Specific interests of the area are affected by the spill. Human population does not live directly or indirectly from the resources provided by sea-related activities. |
| 2 | Area of low importance in terms of environmental resources, leisure and other sea-related activities; Area of local interest. There is low investment that may be affected by the spill; Some interests of the area are affected by the spill. |
| 3 | Area of medium importance in terms of environmental resources, leisure and other sea-related activities; Area of medium regional and national interest. There is medium investment that may be affected by the spill. The spill affects the economy of the area and few economic aspects of neighbouring areas. |
| 4 | Area of high importance in terms of environmental resources, leisure and other sea-related activities; Area of high regional and national interest. Human population lives directly or indirectly from the resources provided by sea-related activities. The economy of the area and neighbouring areas can be affected by the spill; or there is high investment that may be affected by the spill. |
| 5 | Area of extreme importance in terms of environmental resources, leisure and other sea-related activities; Area of very high regional and national interest. There is very high investment and economy of the area that may be affected by the spill. Human population lives directly or indirectly from the resources provided by sea-related activities. |



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

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**Table B1.** Different types of risk of spill incidents.

| Navigation | Type of incident | Risk index |
|---|---|---|
| Ship navigating in restricted waters | Ship-to-ship collision | Restricted Waters – Risk of Spill Incident (Ship to Ship Collision) = $I_{RSI\_CS2S\_restricted}$ |
| | Collision with port facilities | Restricted Waters – Risk of Spill Incident (Collision with Port Facilities) = $I_{RSI\_CPF\_restricted}$ |
| | Grounding | Restricted Waters – Risk of Spill Incident (Grounding) = $I_{RSI\_Gr\_restricted}$ |
| | Fire & Explosion | Restricted Water – Risk of Spill Incident (Fire & Explosion) = $I_{RSI\_F\&E\_restricted}$ |
| Ship navigating in unrestricted waters | Ship-to-ship collision | Unrestricted Waters – Risk of Spill Incident (Ship to Ship Collision) = $I_{RSI\_CS2S\_unrestricted}$ |
| | Foundering and structural failures | Unrestricted Waters – Risk of Spill Incident (Foundering) = $I_{RSI\_Fo\_unrestricted}$ |
| | Grounding during navigation | Unrestricted Waters – Risk of Spill Incident (Grounding during navigation) = $I_{RSI\_GDN\_unrestricted}$ |
| | Drift grounding | Unrestricted Waters – Risk of Spill Incident (Drift Grounding) = $I_{RSI\_DG\_unrestricted}$ |
| | Fire & Explosion | Unrestricted Water – Risk of Spill Incident (Fire & Explosion) = $I_{RSI\_F\&E\_unrestricted}$ |
| | Illegal/Operational Discharges | Unrestricted Water – Risk of Spill Incident (Illegal/Operational Discharges) = $I_{RSI\_IOD\_unrestricted}$ |





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**Table C1.** Classification of probability of ship incidents and correspondence between annual probability and index of probability (obtained from Filipe and Pratas, 2007, and inspired by IMO recommendation – IMO, 2002).

| Probability/ Frequency | Definition | Annual Probability/ Frequency ($P_{annual}$) | Index of Probability ($I_P$) |
|---|---|---|---|
| Very High | Likely to occur once or more per month | 10 to 100 or more | > 7–8 |
| High | Likely to occur once to 10 times per year | 1 to 10 | > 6–7 |
| Medium | Likely to occur once in a period from 1 to 10 years | $10^{-2}$ to 1 | > 4–6 |
| Low | Likely to occur from 0.5 to 50 % within a period of 50 years | $10^{-4}$ to $10^{-2}$ | > 2–4 |
| Very low | Likely to occur from 0.05 to 0.5 % within a period of 50 years | $10^{-5}$ to $10^{-4}$ | 0–2 |





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**Table C2.** Spill incident frequency constants used for ship accidents.

| Restricted Waters | | Unrestricted Waters | |
|---|---|---|---|
| Type of Accident | Accident Frequency per km navigated | Type of Accident | Accident Frequency per km navigated |
| Ship to Ship Collision | $3.52 \times 10^{-7a}$ | Ship to Ship Collision | $1.26 \times 10^{-8a}$ |
| Collision with Port Facilities | $4.22 \times 10^{-7b}$ | Foundering | $9.17 \times 10^{-8b}$ |
| Grounding | $2.83 \times 10^{-7b}$ | Grounding During Navigation | $1.23 \times 10^{-7b}$ |
| | | Drift Grounding | $1.89 \times 10^{-8b}$ |
| Fire & Explosion | $1.78 \times 10^{-7a}$ | Fire & Explosion | $1.78 \times 10^{-7a}$ |
| Illegal/Operational Discharges | – | Illegal/Operational Discharges | $2.49 \times 10^{-5b}$ (annual frequency) |

[a] Value adapted from IAEA (2001).
[b] Value extrapolated based on IAEA (2001) and relations between annual frequencies from Filipe and Pratas (2007).





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**Table C3.** Correction factors related to currents ($I_{curr}$), wind velocity ($I_{wind}$) and proximity to shoreline ($I_{prox}$).

| Property/Correction Factor | Category | Value |
|---|---|---|
| currents velocity ($m\,s^{-1}$) $I_{curr}$ | ≧1.54 (3 knots) | 2.0 |
| | ≧1.03 (2 knots) and < 1.54 (3 knots) | 1.6 |
| | ≧0.51 (1 knot) and < 1.03 (2 knots) | 1.2 |
| | ≧0.36 (0.7 knots) and < 0.51 (1 knot) | 0.8 |
| | < 0.36 (0.7 knots) | 0.4 |
| Wind velocity ($m\,s^{-1}$) $I_{wind}$ | ≧25 (90 $km\,h^{-1}$) | 2.0 |
| | ≧13.89 (50 $km\,h^{-1}$) and < 25 (90 $km\,h^{-1}$) | 1.6 |
| | ≧8.33 (30 $km\,h^{-1}$) and < 13.89 (50 $km\,h^{-1}$) | 1.2 |
| | < 8.33 (30 $km\,h^{-1}$) | 0.8 |
| Proximity to shoreline (m) $I_{prox}$ | ≦11 120 (6 nautical miles) | 2.0 |
| | > 11 120 (6 nautical miles) and ≦14 816 (8 nautical miles) | 1.0 |
| | > 14 816 (8 nautical miles) | 0.8 |





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**Table C4.** Correction factors related to visibility ($I_{visib}$), significant wave height ($I_{wav}$) and ship type ($I_{ship}$).

| Property/Correction Factor | Category | | Type of incident: Ship to ship collision | Collision with port facilities | Foundering | Grounding | Grounding during navigation | Drift Grounding | Fire/ explosion |
|---|---|---|---|---|---|---|---|---|---|
| Visibility (km) $I_{visib}$ | ≥ 1.85 (1 n.m.) | | 0.24 | – | 0.6 | – | – | – | – |
| | < 1.85 (1 n.m.) | | 1.76 | – | 1.4 | – | – | – | – |
| Wave height (m) $I_{wav}$ | ≧2.5 m | | | | 1 | – | 1.4 | 1.78 | – |
| | < 2.5 m | | | | 0.1 | – | 0.6 | 0.22 | – |
| Type of incident $I_{ship}$ | Restricted waters | Tankers | 1.7 | 1 | – | 1.6 | – | – | 0.573 |
| | | Cargo | 2.0 | 1 | – | 1.6 | – | – | 2.656 |
| | | Fishing | 0.3 | 0.7 | – | 0.2 | – | – | 0.3 |
| | Unrestricted waters | Tankers | 1.629 | – | 0.113 | – | 0.612 | 1.6 | 1.629 |
| | | Cargo | 3.343 | – | 3.606 | – | 4.286 | 2.133 | 3.343 |





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**Table D1.** Classification of severity of ship incidents and correspondence between severity and index of severity.

| Severity degree | Impacts | | | Severity Index ($I_S$) |
|---|---|---|---|---|
| | Human health | Environment | Socio-economical activities | |
| Catastrophic | Catastrophic number of injuries, fatalities and physical disabilities | Catastrophic and permanent damage to the marine flora and fauna. | Affecting in a catastrophic scale and for long periods of time | > 7–8 |
| Extreme | Extremely number of injuries, fatalities and physical disabilities | Extreme and permanent damage to the marine flora and fauna | Affecting at extreme scale and for long periods of time | > 6–7 |
| Very high or very serious | Very high number of injuries, fatalities and physical disabilities | Very serious and almost permanent damage to the marine flora and fauna. | Affecting at very high scale and for long periods of time | > 5–6 |
| High or serious | High number of injuries, or physical disabilities | Long term damage to the marine flora and fauna. High cost of measures needed to restore the resources affected by the spill | Affecting at high scale and for long periods of time | > 4–5 |
| Medium or moderate | Medium number of injuries (unlikely to result in physical disabilities) | Medium term damage to the marine flora and fauna. Moderate cost of measures needed to restore the resources affected by the spill | Affecting at medium scale and for long periods of time | > 3–4 |
| Little or slight | Little number of injuries | Short term damage to the marine flora and fauna. Low cost of measures needed to restore the resources affected by the spill. | Affecting at little scale and for long periods of time | > 2–3 |
| Very little or very slight | Very little number of injuries. Very little first aid assistance | Very short term damage to the marine flora and fauna. Very low cost of measures needed to restore the resources affected by the spill. | Affecting at little scale and for long periods of time | > 1–2 |
| Insignificant | No reported harm to human health | No damage to the marine flora and fauna. No restoration measures needed | No effects | > 0–1 |





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**Table D2.** Average amount of spilled oil per incident type and ship type.

| Type of incident | Equation $Q$ = oil amount (ton); DW = Deadweight (DWT) | | |
|---|---|---|---|
| | Tanker (crude) | Fishing Vessels (diesel) | Cargo (bunker) |
| Ship to ship collision | $Q = 1 \times 10^{-7}\,\mathrm{DW}^2 + 0.0327\,\mathrm{DW}$ | $Q = 6$ | $Q = 60$ |
| Collision with port facilities | $Q = 5 \times 10^{-8}\,\mathrm{DW}^2 + 0.0134\,\mathrm{DW}$ | $Q = 3$ | $Q = 25$ |
| Foundering | $Q = \mathrm{DW}$ | $Q = 12$ | $Q = 1300$ |
| Grounding | $Q = 5 \times 10^{-7}\,\mathrm{DW}^2 + 0.1362\,\mathrm{DW}$ | $Q = 2$ | $Q = 130$ |
| Fire & Explosion | $Q = 0.8\,\mathrm{DW}$ | $Q = 10$ | $Q = 100$ |
| Illegal/operational discharges | $Q = 25$[a] | $Q = 3$[a] | $Q = 7$[a] |

[a] Values used are the worst case values/highest values for the different types of operational/illegal discharges.





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**Table D3.** Quantification of severity index, based on oil amount ship type.

| Ship type | Unrestricted waters | Restricted waters |
|---|---|---|
| Crude (tanker) | $I_{s\_unsrestricted} = 0.4037\ln(Q) + 1.9534$<br>$I_{s\_unrestrictedmin} = 0$; $I_{smax} = 8$ | $I_{s\_restricted} = 0.4693\ln(Q) + 1.9903$<br>$I_{s\_unrestrictedmin} = 0$; $I_{smax} = 8$ |
| Diesel (fishing) | $I_s = 0.4343\ln(Q) + 1.301$<br>$I_{s\_restrictedmin} = 0$; $I_{smax} = 7$ | $I_s = 0.4689\ln(Q) + 1.666$<br>$I_{s\_restrictedmin} = 0$; $I_{smax} = 8$ |
| Bunker (cargo) | $I_s = 0.3996\ln(Q) + 1.9285$<br>$I_{s\_restrictedmin} = 0$; $I_{smax} = 8$ | $I_s = 0.4517\ln(Q) + 2.1643$<br>$I_{s\_restrictedmin} = 0$; $I_{smax} = 8$ |





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**Table D4.** Subtracting correction factor based on spill site used, in function of ship type.

| Ship Type | Equation for Correction Factor ($F_{SS}$) |
|---|---|
| Fishing (Diesel) | $F_{SS} = \frac{8}{15} \cdot 0.3 \cdot D_{SS}$ |
| Tanker (Crude) | $F_{SS} = \frac{8}{15} \cdot 0.2 \cdot D_{SS}$ |
| Cargo (Bunker) | $F_{SS} = \frac{8}{15} \cdot 0.1 \cdot D_{SS}$ |





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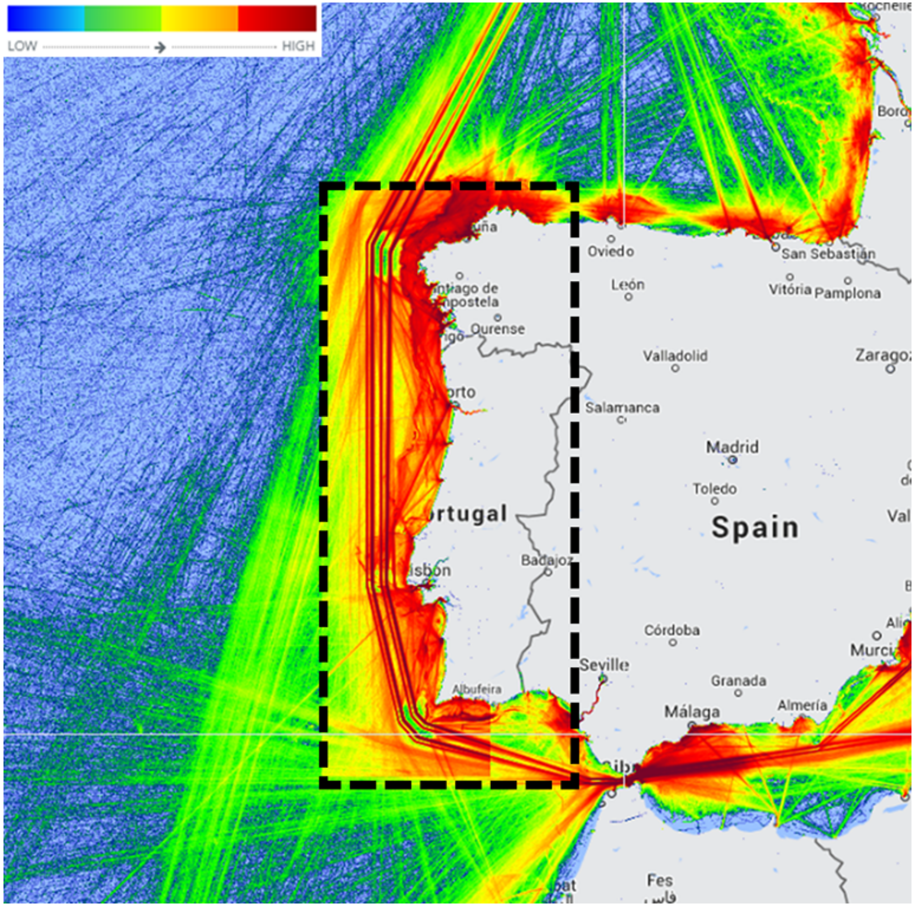


**Figure 1.** Ship density map around the pilot area in 2014. The white rectangle represents the area considered in this work to study the shoreline contamination risk in the Portuguese continental coast (source: marinetraffic.com).





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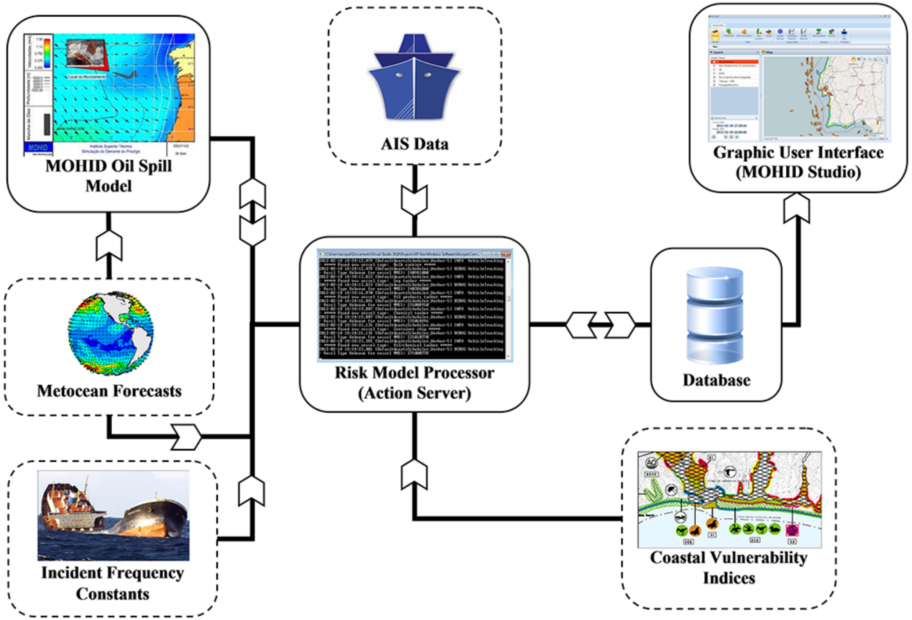


**Figure 2.** General information workflow in the risk modelling system.





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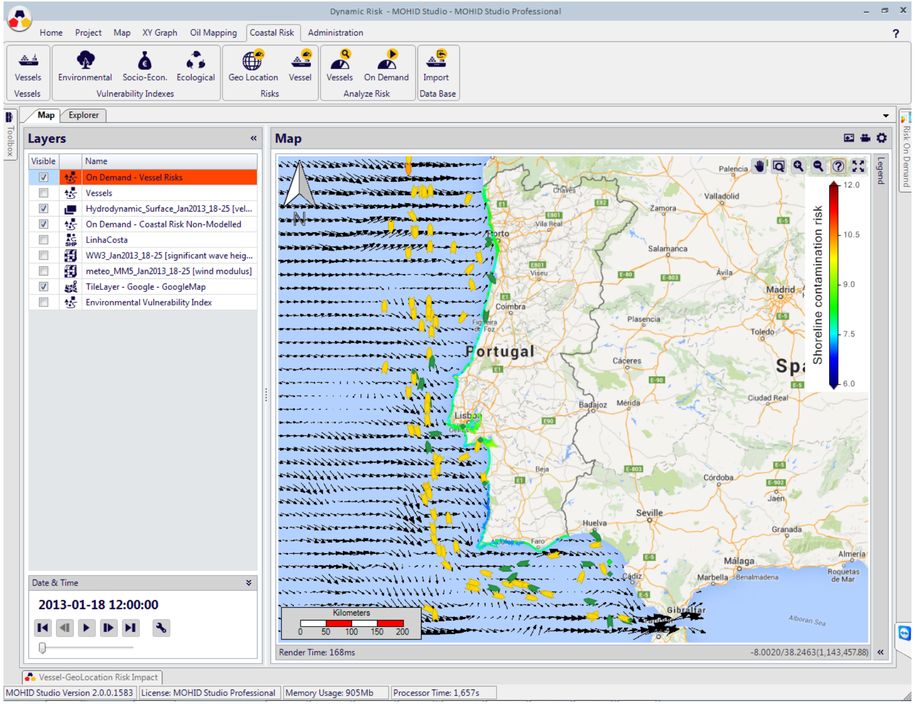


**Figure 3.** Graphic User Interface layout, with simultaneous visualization of ship incident risks, shoreline contamination risks, surface water velocity and Google map layer. Ship incident risk colors presented in categorized view (green, yellow, orange and red colors).



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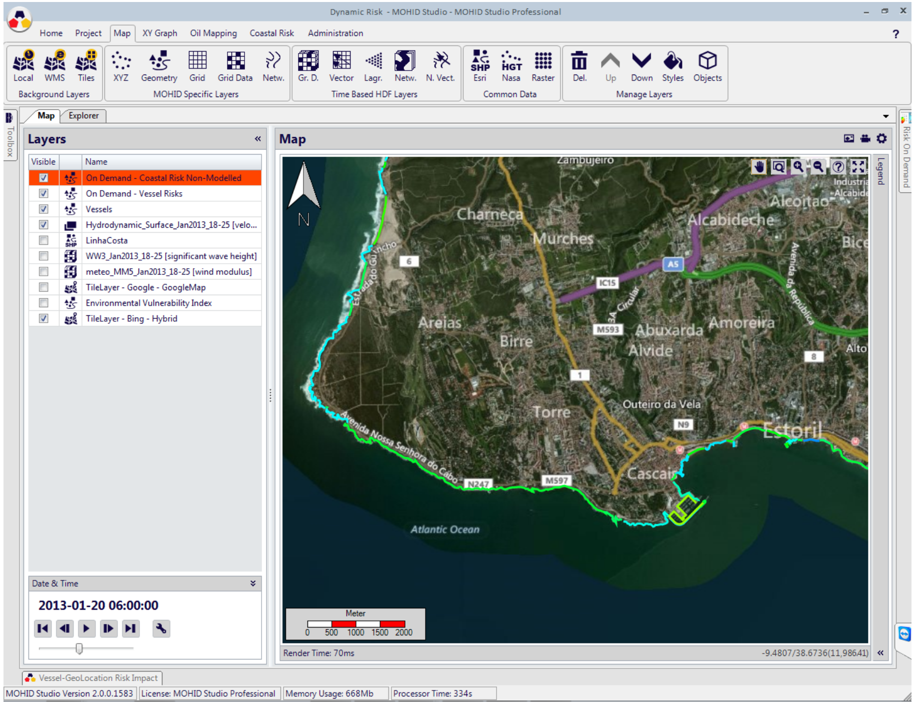


**Figure 4.** Zoomed image of the Graphic User Interface for the Lisbon area – simultaneous visualization of coastal sensitivity index and Bing Hybrid map layer.





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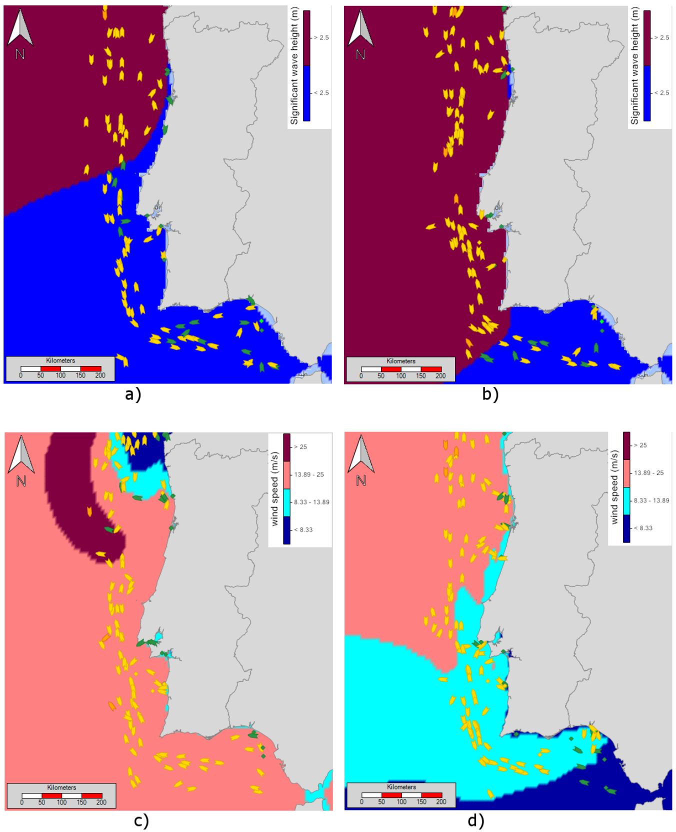


**Figure 5.** Ship incident risk levels (green ships mean lower risk, yellow means medium risk and orange ships mean higher risk) in the pilot area with background metocean conditions used. **(a)** and **(b)** significant wave height in 18 January 2013, 12:00 and 19 January 2013, 00:00 respectively; **(c)** and **(d)** wind speed in 19 January 2013, 06:00 and 22 January 2013, 06:00, respectively.

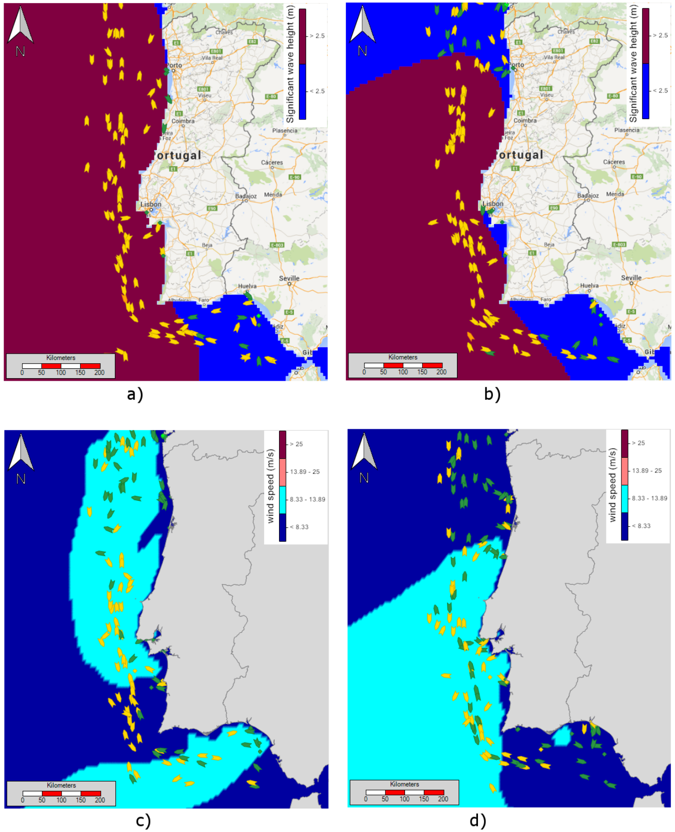


**Figure 6.** Ship incident risk levels (green ships mean lower risk, yellow means medium risk and orange ships mean higher risk) in the pilot area with background metocean conditions used. **(a)** and **(b)** significant wave height in 18 June 2013, 12:00 and 19 June 2013, 00:00 respectively; **(c)** and **(d)** wind speed in 19 June 2013, 06:00 and 22 June 2013, 06:00, respectively.

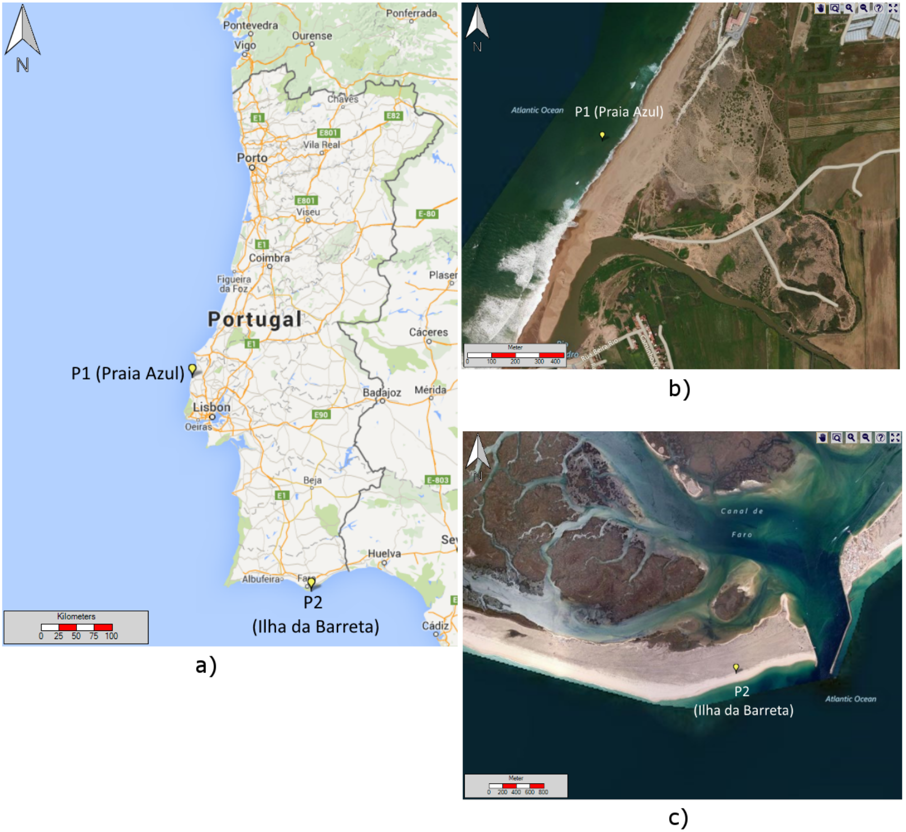


**Figure 7.** Location points for the shoreline contamination risk detailed study – **(a)** is the location in Portuguese continental map; **(b)** is the aerial view from P1 (Praia Azul) and **(c)** is the aerial image from P2 (Ilha da Barreta).





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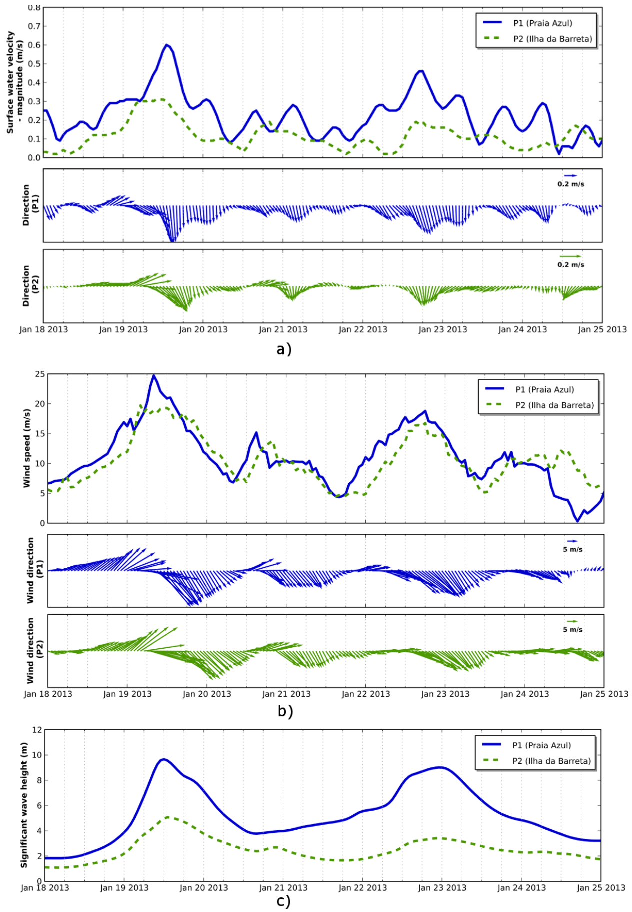


**Figure 8.** Metocean conditions used in risk model, in points P1 and P2. Surface water velocity, wind velocity and significant wave height.





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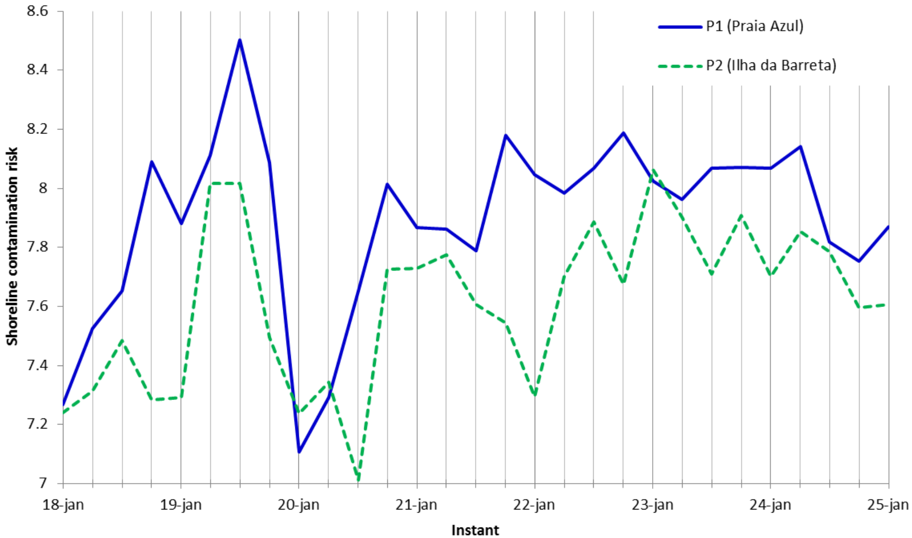


**Figure 9.** Evolution of shoreline contamination risk in P1 and P2 between 18 and 25 January 2013.

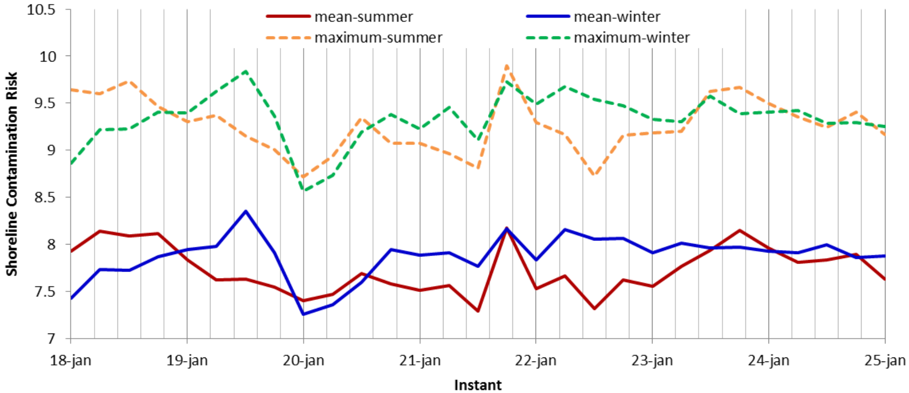


**Figure 10.** Integrated shoreline contamination risk for the whole pilot area, with AIS vessel information between 18 and 25 January 2013, and using winter metocean model conditions (in the same period) and summer metocean model conditions (from 18 to 25 June 2013).

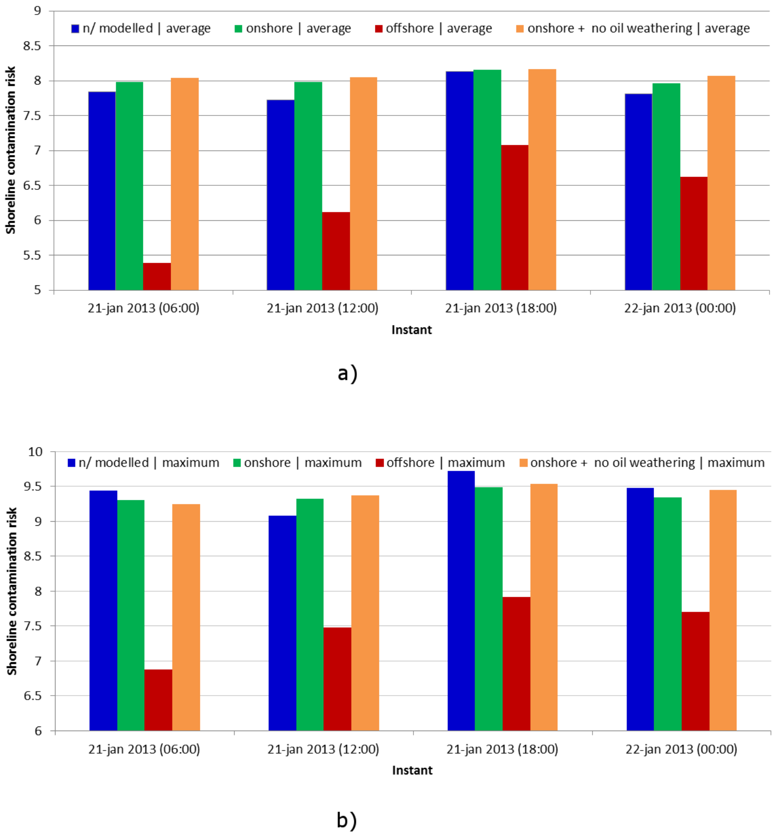


**Figure 11.** Integrated shoreline contamination risk levels at different time instants from 21 and 22 January 2013. Results presented in mean **(a)** and maximum **(b)** values for the shoreline in the whole pilot area studied. Shoreline risk levels computed with 4 different approaches: non-modelled approach; modelled approach using onshore wind; modelled approach using offshore wind; modelled approach without oil weathering processes, using onshore wind.





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